A review of tectonic models for the rifted margin of Afar: implications for continental break-up and passive margin formation

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Running title (5 words, will appear on top of each page): Tectonics of the Afar margin

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Abstract

The Afar region represents a unique opportunity for the study of ongoing rift development and the various phases of continental break-up. In this work we discuss the geological and geomorphological characteristics of the Western Afar Margin (WAM) and the various scenarios proposed for its evolution. A drastic decline in topography and crustal thickness from the Ethiopian Plateau into the Afar Depression, as well as a series of marginal grabens and a general presence of antithetic faulting characterize the WAM. Present-day extension is mostly accommodated at the rift axis in Afar, yet the margin is still undergoing significant deformation.

Models for the evolution of the WAM involve either isostatic loading effects due to erosion, rift-induced block rotation, large-scale detachment fault development or crustal flexure due to lithospheric stretching or magmatic loading. This wide variation of potential mechanisms for WAM development may reflect a general structural variation along the margin and in Afar, involving different stages of rift formation and possibly indicating two distinct pathways leading to continental break-up.

Yet in order to better understand the rifting mechanisms and to fully exploit the research potential of the region, further assessment of the WAM and its relation to the Afar will be necessary. The findings of such future work, combined with data from rifts and passive margins from around the globe will be of great importance to assess the processes involved in continental breakup and to better constrain the sequence of events leading from initial rifting to break-up and oceanic spreading.

1. Introduction

One of the crucial processes in plate tectonics is the rifting and eventual breaking up of continents, followed by the opening a new ocean basin with a passive continental margin on either side. Rifts and passive margins have been studied extensively for economic reasons, in particular for their vast oil and gas reserves (e.g. Levell et al. 2011; Zou et al. 2015), their rich archives on global environmental change (e.g. Haq et al. 1987; Catuneanu et al. 2009; Kirschner et al. 2010; Catuneanu & Zecchin 2013) and their associated natural hazards (Brune 2016). Yet the structural evolution of continental break-up and the processes involved remain poorly understood (e.g. Peron-Pinvidic et al. 2013). The main reasons involve accessibility: significant parts of (aborted) rifts or passive margins are generally situated deep below sea level and relevant structures are often covered by thick sequences of clastic sediments and evaporites (Divins 2003; Brune 2016), thus posing significant challenges for scientists and exploration geologists alike (e.g. Argent et al. 2000; Law et al. 2000; Oakman 2005; Levell et al. 2011; Jones & Davison 2014).

The Afar region, which forms the triple junction between the East African, Red Sea and Gulf of Aden rift systems (Fig. 1), provides geologists with a unique research opportunity, as it represents one of the rare locations where active continental break-up and the on-going transformation from rifts to passive margins can be examined on land (Varet 2018). In recent years, much attention has focused on understand mechanisms and time scales of magma injection in the rift axis of Afar, where phases of intense volcanism and focussed seismicity occur along discrete segments of the rift axis (e.g. Wright et al., 2005; Barnie et al., 2016). These may represent embryonic spreading centres heralding the final separation between Africa and Arabia (e.g. Barberi et al. 1970, Barberi & Varet 1977; Hayward & Ebinger 1996; Ebinger et al. 2010, Fig. 1a). By contrast, the margins of the Afar rift remain poorly studied.

This review paper is mainly focused on the Western Afar Margin (WAM, Figs. 1, 2), which represents a major fault zone separating the Afar Depression from the Ethiopian Plateau and marks a drastic reduction in topography (from 2500-3000 m to 800-100 m and locally below sea level, Mohr 1983, Figs. 1, 3) and crustal thickness (from ca. 40 km down to 23-16 km, Makris and Ginzburg, 1987; Hammond et al. 2011). A remarkable series of basins (referred to as “marginal grabens”, Mohr 1962, Fig. 1b) aligns along the rifted margin. These fault-bounded basins, a unique feature for along rifted margins, are tectonically active, posing severe seismic hazards to the local population (Gouin 1979; Ayele et al., 2007).

Previous authors have proposed various contrasting structural models to explain the evolution and architecture of the WAM and the origin of the marginal grabens, from rollover structures due to a large-scale detachment faults (e.g. Tesfaye & Ghebreab, 2013), erosion-induced isostatic adjustment (Mohr 1962) to lithospheric flexure caused by magmatic loading (e.g. Wolfenden et al. 2005). It is clear that the development of the WAM and its marginal grabens is linked to plate extension, yet to date no scientific consensus has been reached over which processes govern the system.
The aim of this paper is therefore to provide an overview of the various concepts proposed for the structural evolution and architecture of the WAM and its marginal grabens, how these concepts relate to the available field evidence and how they may fit in the large-scale evolution of Afar. We furthermore propose strategies and techniques to improve our knowledge of the area in order to better understand rift and passive margin evolution.

2. Regional geological setting

The Afar forms a triangular zone of highly extended lithosphere with a relatively low surface topography, locally even below sea level. The Afar is bordered by the Ethiopian Plateau to the west, the Somalian Plateau to the south (Mohr 1983) and the Danakil and Ali-Sabieh/Aïsha Blocks to the NE and east (Kidane 2015, Fig. 1). From the east, the Gulf of Aden enters the Afar at the Gulf of Tadjura, initiating continental break-up there (e.g. Makris & Ginzburg 1987; Manighetti et al. 1997; 1998). In the north, the Red Sea spreading system steps laterally over the Danakil Block into the Gulf of Zula and northern Afar. From there, the Danakil Depression and its continuation to the SE represent the second arm of the current Afar triple junction (Fig. 1, inset). Along the axis of this rift zone, deformation, earthquake activity and volcanism are currently localized along discrete magmatic segments, where a significant proportion of extension occurs by magma intrusion (e.g. Barberi et al. 1970, Barberi & Varet 1977; Hayward & Ebinger 1996; Ebinger & Casey 2001; Wright et al., 2006; Ebinger et al. 2010). The Danakil rift links up with the Gulf of Aden structures through a series of en-echelon and overlapping rifts in central and eastern Afar (e.g. Abbate et al. 1995; Manighetti et al. 1998, 2001; Muluneh et al. 2013; Doubre et al., 2007; Pagli et al. 2018). The Main Ethiopian Rif in the south forms the third rift branch, and is separated from the Red Sea-Gulf of Aden system by the Tendaho-Gobaad Discontinuity (e.g. Wolfenden et al. 2004).

The development of Afar initiated with the eruption of extensive flood basalts during a ca. 1 Ma interval around 30 Ma (Hoffman et al. 1997), an event associated with the emplacement of one or multiple mantle plumes (Rooney et al. 2011; 2013, and references therein). These basalts, referred to as the trap series, cover a peneplain surface that extends into Yemen and that is characterized by laterites, indicating a long period of tectonic stability at low elevation (Abbate et al. 2015). The emplacement of the traps was followed by the onset of rifting in the Afar between 26-31 Ma (Wolfenden et al. 2005). In the Gulf of Aden and Red Sea, extension started at ca. 35 Ma and ca. 23 Ma, respectively (Szymanski et al. 2016; Leroy et al. 2010 and references therein).

Continental rifting was followed by oceanic spreading around 17.6 Ma or even 20 Ma at the easternmost sector of the Gulf of Aden and progressed westward (Manighetti et al. 1997; d'Acremont et al. 2006; 2010; Autin et al. 2010; Fournier et al. 2010; Leroy et al. 2010). By contrast, break-up in the Red Sea is dated at around 5 Ma (Bosworth et al. 2005; Cochran 2005; Augustin et al. 2014 and references therein), but may have initiated as early as 12 Ma (Izzeldin 1987). In the Afar, a decreasing trend in the age of earliest rift-related volcanism from north to south, indicates that Red Sea rifting propagated southward until ca. 11 Ma (Zanettin & Justin-Visentin 1975; Wolfenden et al. 2005; Ayalew et al. 2006). Around this time, the Main Ethiopian rift developed in the south forming the third arm of the current triple junction (Wolfenden et al., 2004).

This late development of the Main Ethiopian rift, which in contrast to the other rift arms likely propagated to the SW, away from Afar (Bonini et al. 2005; Abebe et al. 2010b), confirms the notion that the Afar should not be seen as an example of a classic RRR-triple junction (e.g. Barberi et al. 1972; Varet 2018). Furthermore, the Danakil block, which is strongly extended and previously a part of the Red Sea rift valley floor (Morton and Black 1975; Collet et al. 2000; Redfield et al. 2003), started an anticlockwise rotation due to the development of the Danakil depression around 9 Ma (e.g Eagles et al. 2002; McClusky et al. 2010). The Danakil Block thus became an additional conjugate margin to the WAM, next to the larger Yemen margin. In the meantime, the Ali-Sabieh/Aïsha block underwent a simultaneous clockwise rotation (Kidane 2015).

As extension proceeded in the Afar, deformation generally shifted from the rift margins to the rift axes, possibly in a stepwise succession reflected in three distinct volcanic phases (Zanettin & Justin-Visentin 1975, Wolfenden et al. 2005). During this process, magmatism and deformation became highly focuses along discrete spreading sectors (e.g. the Wonji Fault belt in the Main Ethiopian Rift and the Danakil Ridge in the Danakil Depression). These sections, where deformation is strongly localized, can be considered the loci of embryonic oceanic spreading centres, and the focus of ongoing continental break-up processes (e.g. Barberi et al. 1970, Barberi & Varet 1977; Hayward & Ebinger 1996; Ebinger & Casey 2001; Ebinger et al. 2010).

3. The Western Afar Margin

3.1. General tectonic characteristics

The WAM, which stretches roughly N-S following a sigmoidal trace between ca. 9°30'N-14°N, marks a sharp decline in topography, from 3000-3500 m to ca. 500 m, or even below sea level in the northernmost parts of the Afar (Fig. 1). This decrease in altitude is accompanied by a decrease in crustal thickness from some 40 km below the Ethiopian Plateau to 25 km in southern Afar, down to 15 km in the Danakil Depression (Makris and Ginzburg, 1987; Bastow and Keir, 2011; Hammond et al., 2011). The margin is characterized by normal faulting and tilted blocks, as well as the presence of unique marginal grabens (e.g. Abbate & Sagri, 1969; Justin-Visentin & Zanettin 1974; Beyene & Abdelsalam, Abbate et al. 2015; Corti et al. 2015a; Stab et al 2016, Figs. 1-4a-c) and ongoing seismic activity (e.g. Gouin 1970, 1979; Ayele et al., 2007; Craig et al., 2011; Goitom et al., 2017; Illsley-Kemp et al., 2018, Fig. 1).

3.2. Antithetic faulting and block rotation

The structural architecture of the WAM is dominated by a pervasive style of antithetic normal faulting (i.e. normal faults dipping away from the rift basin, here to the west) and the widespread occurrence of eastward tilted fault blocks with dips increasing towards Afar (Baker et al. 1972, Fig 4a-d). In the Arabati area for instance (i.e. the WAM east of Dessie, Fig. 1) the margin consists of 1-5 km wide fault blocks that are increasingly tilted eastward, from 10˚ to 35˚, although much higher dips are recorded in the Afar Depression to the NE (Mohr 1983; Stab et al. 2016). Similar observations are reported by Abbate & Sagri (1969), who found fault blocks dipping 30-40 degrees to the NE and faults dipping 60˚-70˚ the SW in the area north of Dessie (Figs. 1, 4a-c). Also, feeder dikes from the pre-rift trap basalts are tilted in the same fashion (Abbate & Sagri 1969, Justin-Visentin & Zanettin 1974). It is worth noting that dike swarms tend to be parallel to the margin (Mohr 1971; Megrue et al. 1972), although Barberi et al. (1974) stress the presence of transverse dikes and lineaments, as well the general right-stepping en-echelon offset of the transition between the WAM and the Afar Depression (Fig. 2).

Wolfenden et al. (2005) report a similar situation between Dessie and the southern end of the WAM: synthetic faults and westward dipping strata west of the marginal grabens versus antithetic faulting with eastward dipping blocks on the Afar side. Dips are similar to those reported to the north (10˚-45˚). Note that antithetic faulting is to some extent also present in the easternmost section of the Southern Afar Margin (SAM) (Tesfaye et al. 2003, Fig. 1), that is otherwise dominated by synthetic (i.e. northward) normal faulting (Fig. 4e). Other examples of antithetic faulting are found SE of the Danakil Block (Figs. 1, 4f, Le Gall et al. 2011), as well as on the Yemen-Red Sea margin (Davison et al. 1994, 1998; Geoffroy et al.

1998). Yet no large and well-defined marginal grabens as observed along the WAM occur in these areas (Fig. 1, section 3.3).

3.3. Marginal grabens

Next to the antithetic faulting and associated tilted fault blocks, the WAM harbours a series of remarkable fault-bounded basins. The names and extend of these basins are not always clearly defined, as different authors use different names for different (sub)basins, which is especially confusing in the northernmost part of the WAM. The situation is not improved by the fact that place names written in the Ethiopian alphabet are not readily transferable in the latin alphabet (Gouin, 1979) and have changed over time for political reasons. An attempt to summarize terminology is presented in table 1 and coarse basin extents are outlined in Fig. 2. In the following we tend to follow the convention proposed by Abbate et al. (2015). Note that the Damas basin (Tesfaye & Ghebreab, 2013), which shares the characteristics of the other basins, is not strictly part of the WAM, but is situated at the Red Sea margin and linked to the Buia basin by a transfer zone (Drury et al. 2006, Fig. 1). Also, the status of the Buia Basin as a marginal graben can be contested, as it practically forms the continuation of the Danakil rift axis (Figs. 1, 2).

The marginal basins follow the curving N-S trend of the WAM, which is ca. N-S between 13-14° N, NNE-SSW between 14°-12°30'N, NNW-SSE between 12°30'N-10°N (or even 9°30'N, Wolfenden et al. 2005). However, individual basins are oriented ca. NNW-SSE and arranged in a right-stepping pattern, although the Robi Basin and the northern part of the Kobo basin have a NNE-SSW orientation (Fig 2). This general NNW-SSE orientation is oblique to the overall trend of the margin, but roughly parallel to the rift axis in Afar and may be due to the reactivation of a Neoproterozoic (Pan-African) tectonic grain, possibly in combination with oblique extension (e.g. Baker et al. 1972; Drury et al. 1994; Chorowicz et al. 1999; Talbot and Ghebreab 1997; Ghebreab and Talbot 2000). Transfer zones with complex fault structures link up the marginal basins into a continuous system that covers most of the WAM.

The basins themselves are some 10-20 km wide and several tens of km in length, although at various places they are poorly developed and various small (sub)basins can be distinguished (Fig. 2). The sedimentary infill consists of alluvial deposits of at least Pliocene-Quaternary age (e.g. Kazmin 1972; Chorowicz et al. 1999). In the Buia basin to the north, these deposits can be up to 550 m thick (Ghinassi et al 2015; Sani et al. 2017). In contrast, sediment thicknesses in the Borkenna basin to the south are limited (Abbate et al. 2015). However, there is a general lack of data on the thickness, type and age of the sediments in the marginal grabens and no seismic sections or well logs are published (Tesfaye and Ghebreab, 2013), so that there are little constraints on the timing of basin formation.

As pointed out by Mohr (1978), the altitude of the marginal graben floors increases towards the south, a feature well visible on topographic sections (Fig. 3). In the northernmost basin (Garsat), the basin floor lies at ca. 500 m, whereas the basin floor of e.g. the Hayk and Borkenna basins are situated at ca. 1500 m altitude. The sections also nicely illustrate that in the north, the distance between the marginal grabens and the plateau margin amounts to various tens of kilometres (Fig. 3a, b). This distance decreases towards the south so that the Borkenna Basin lies immediately adjacent to the margin (Fig. 3e), which is in line with a southward propagation of rifting (e.g. Wolfenden et al. 2005; Ayalew et al. 2006); the older northern part of the WAM seemingly experienced more erosion and associated retreat of the plateau margin (Zanettin & Justin-Visentin 1975).

It is worth stressing that although the antithetic faulting typical for the margin can to a degree be observed at different locations in the region (see section 3.2), the presence of such well-developed marginal grabens are to our knowledge a unique feature of the WAM.

3.4. Seismicity

Afar also exhibits a high degree of seismic activity of magnitudes up to ~M6.5, that pose significant direct and indirect hazards (Gouin 1979; Abebe et al., 2010a). Most of these earthquakes can be linked to the (developing) spreading centres in the Afar Depression, the Red Sea, Gulf of Aden and Main Ethiopian Rift (Fig. 1). However, an important belt of seismic activity occurs along the WAM and numerous significant seismic events have been recorded in the area (e.g. Gouin 1970, 1979; Ayele et al., 2007; Craig et al., 2011; Goitom et al., 2017; Illsley-Kemp et al., 2018).

The first historical account of an earthquake in Ethiopia occurred in the northern part of the WAM in 1431-1432 (Gouin, 1979). This has been followed by reports of several 10s of significant earthquakes in the 15^{th} - 20^{th}centuries (Gouin, 1979). Notable events are the swarm of earthquakes during 1841-1842 which triggered a landslide that destroyed Ankober, and the 1961 earthquake swarm which destroyed Majete and caused significant damage to Karakore (Gouin, 1979). The National Earthquake Information Centre (NEIC) provides constraints on earthquakes >M4 since 1973. The catalog shows earthquakes distributed along the WAM (Fig. 1), though earthquake numbers and seismic moment release is highest in the northern WAM (Keir et al., 2013).

Moment tensor inversion of globally recorded waveforms suggests most earthquakes are less than 10 km depth, though some earthquake do occur down to ~20 km (e.g. Craig et al., 2011). This depth distribution is consistent with that determined using local seismic networks (Illsley-Kemp et al., 2018; Keir et al., 2006). Earthquake focal mechanisms are mostly of normal faulting type with the majority of T-axes scattered by +- 40 degrees either side of N95 degrees (e.g. Illsley-Kemp et al., 2018; Craig et al., 2011; Ayele et al., 2007). A few strike slip earthquakes are also observed (Illsley-Kemp et al., 2018).

These recurring seismic events pose severe risks to the population living in the agriculturally attractive marginal grabens and along the plateau scarps of the WAM, especially due to the presence of steep, easily destabilized slopes (e.g. Abebe et al., 2010a; Meaza et al. 2017 and references therein). The ongoing tectonic activity along the western margin of the Afar also suggests that not all the extension has been focused to the rift axis (Illsley-Kemp et al., 2018). Therefore, the rifted margin of Afar has not yet evolved into a true “passive” margin (Fig. 1).

Yet the driving force for deformation and earthquake generation remains unclear. Authors have proposed that stress focusing along the WAM caused by a gradient in crustal thickness, magmatic loading of the rift, as well as sedimentary loading within the rift and the marginal grabens may play a role in focusing extensional stresses (e.g. Wolfenden et al. 2005; Tesfaye & Ghebreab 2013), but little data to support these hypotheses is available. For instance, most earthquake locations and depths are not constrained to a sufficient resolution required to link an event to a specific fault.

Exceptions to this are recent analysis from the Garsat area which suggests that seismicity is situated on the antithetic eastern boundary fault of the marginal graben system (Illsley-Kemp et al. 2018). In addition, the surface deformation of the 1961 Karakore seismic events was concentrated along the eastern boundary fault of the Borkenna basin (Gouin 1979). When examining the marginal grabens in more detail, it often appears that the eastern boundary fault scarps are characterized by fresher, steeper and less eroded morphology than their western counterparts, where the fault trace may even be absent (Fig. 1c, d). This likely reflects a more intense, recent fault activity on the eastern, antithetic faults.

4. Models for the development of the structural architecture along the WAM

Below we present an overview of the various tectonic mechanisms proposed for the development of the structural framework of the WAM, which are subsequently linked to the tectonic evolution of the Afar and the Red Sea rift. Early models involve erosion of the plateau margin (Mohr 1962) or block rotation due to crustal creep (Black et al. 1972). Other authors have suggested that extension in Afar is principally accommodated by large-scale detachment faulting (e.g. Morton and Black 1975; Chorowicz et al. 1999; Tesfaye & Ghebreab 2013, Stab et al. 2016). Alternative models involve marginal flexure (Abbate and Sagri 1969), possibly triggered by magmatism during the development of Afar (e.g. Wolfenden et al. 2005). In the following sections we aim to describe the main aspects of each of the proposed tectonic models as well as their implications and predictions.

4.1. Erosion of the plateau margin

In an early paper, Mohr (1962) proposed that the Borkenna Graben in the southern section of the WAM may have formed simply due to isostatic compensation after material was removed by erosion of the plateau margin (Fig. 5a-d). According to the model, post-trap extension caused rifting. Subsequent erosion and crustal readjustment formed the eastern boundary fault, followed by the western boundary fault. Although the author states in a later publication, without further explanation, that the model is not realistic (Mohr 1967), its merit is that it does take into account buoyancy effects due to surface processes. Another process affecting tectonics along the WAM may be sedimentary (or magmatic) infill and loading of the marginal grabens (Tesfaye and Ghebreab 2013), which is known to have an important effect on rift tectonics (e.g. Burov & Cloetingh 1997; Burov & Poliakov 2001; Corti et al. 2013; Zwaan et al. 2018).

4.2. Crustal creep and rollover fault models

Black et al. (1972) suggested that brittle deformation along the Afar margins may be controlled by underlying (lower) crustal creep during extension (Fig. 5e, f). However, which parameters control whether faulting is synthetic or antithetic remains unclear. Kazmin et al. (1980) and Zanettin & Justin-Visentin (1975) consider the possibility that all faulting is initially synthetic, after which the easternmost fault blocks are so far rotated towards the Afar that fault throw is reversed and the previously synthetic faults become antithetic. A mechanism other than continued tectonic thinning to explain this massive block rotation is however not provided.

4.3. Detachment fault models

In a subsequent paper, Morton and Black (1975) proposed two more elaborate models in which synthetic and antithetic faults (in the case of the WAM eastward and westward dipping faults, respectively) may interact, leading to the formation of a marginal graben in a rollover fault setting (Fig. 5g-h). In this view, the first option is a scenario dominated by a large antithetic (detachment) fault and a marginal graben (i.e. a “compensation graben”, Faure & Chermette 1989) forms due to minor synthetic faulting. The other option involves a large synthetic (detachment) fault and a graben forming due to secondary antithetic faults. In both models, deformation is strongly focused along the detachment fault and the basinward part of the crust is dominated by antithetic faulting. Note however, that the timing of synthetic fault initiation is different in both cases (Fig. 5g-h). Block rotation is suggested to increase towards Afar as a result of enhanced extension towards the rift axis.

4.3.1. Eastward dipping detachment model (Tesfaye & Ghebreab 2013)

Tesfaye and Ghebreab (2013) suggest an eastward dipping detachment model for Afar (Fig. 6a, b). The authors based the analysis primarily at the northernmost part of the WAM next to the Gulf of Zula (e.g. Drury et al. 1994; Talbot and Ghebreab 1997; Ghebreab and Talbot 2000, Fig. 6c). The WAM is interpreted as the original breakaway zone along pre-existing Neoproterozoic (Pan-African) weaknesses (Fig. 8a), now marked by its strong decline in topography and crustal thickness. After a first phase of asymmetrical deformation, the current situation is one of symmetrical stretching (Fig. 6b). Within this context, the northernmost marginal grabens, which are situated closest to the Afar rift axis, would be the oldest and most evolved structures (Tesfaye & Ghebreab 2013). Their low altitude (even below sea level) is due to the strongly thinned crust in the northern Afar (15 km versus 25 km to the south, Bastow & Keir 2011, Hammond et al. 2011). Such a topographic decline towards the north can also be observed along the (northern) Danakil block, which is interpreted as a core complex exhumed along a large-scale detachment (Talbot and Ghebreab 1997). The marginal grabens are then associated with the large-scale detachment fault and although not specifically stated by the authors, must as such be part of a rollover structure (Figs. 7a, 8c).

The idea that the oldest basins are found in the north fits with the observation that volcanism and associated rifting initiated in the northern part of the WAM and propagated southward (Zanettin and Justin-Visentin 1975; Ayalew et al. 2006). A problem however, may be the actual presence of the main detachment. Although such structures are reported from Eritrea, their existence is contested by Abbate et al. (2002), arguing that there is no evidence to support a large-scale detachment. Also, if present, an eastward dipping detachment should account for most of the deformation and seismicity in the area (Abbate and Sagri 1969). Yet the western margins of the Borkenna and other basins are strongly eroded, whereas fresh(er) fault scarps tend to occur along the eastern boundary faults of many WAM basins (Figs. 2, 3). Seismic activity seems to be focused on the eastern boundary faults, at least in the northern part of the WAM (Illsley-Kemp et al. 2018), but the geomorphological data suggests this observation can be extrapolated to the south. For instance the surface deformation of the 1961 Karakore seismic event was concentrated along the eastern boundary fault of the Borkenna basin (Gouin 1979).

4.3.2. Two-phase eastward dipping detachment model (Chorowicz et al. 1999)

Chorowicz et al. (1999) proposed a model somewhat similar to the Tesfaye and Ghebreab (2013) model in that it involves large eastward dipping detachments, yet it incorporates multiple phases of deformation associated with the motion of the Danakil block (Fig. 7). By means of radar imagery combined with fieldwork in the Borkenna basin, the authors interpret an initial phase of sinistral strike-slip motion in the early to middle Miocene due to a general N20˚ extension (Fig. 7a). The strike-slip deformation reactivated Pan-African weaknesses leading to the formation of proto-marginal grabens as releasing bends along the whole of the WAM (Fig 7a). A subsequent minor phase of diffused NW-SE extension seems to fit with deformation in the Main Ethiopian Rift to the south. The final deformation phase concerns the Pliocene-Quaternary and involves eastward motion and opening of the marginal grabens due to gravity-induced detachment of large crustal blocks along the WAM as the Danakil block rotates away and Afar opens (Fig. 9b-d).

Chorowicz et al. (1999) are so far the only authors invoking an initial strike-slip motion during the formation of the WAM. The opening of the Main Ethiopian Rift is indeed supposed to have taken place in Miocene times (ca. 11 Ma, Wolfenden et al. 2004). The rotation of the Danakil block is a well-established and currently active phenomenon, although the amount and timing of rotation is disputed (Collet et al., 2000; Eagles et al 2002; McClusky et al. 2010).

There are however some objections to the Chorowicz et al (1999) model. Wolfenden et al. (2005) have criticized the choice of fieldwork area since most of the data are gathered to the north of the Borkenna Basin, in the Dese-Bati accommodation zone that links the Borkenna basin with the Hayk Basin to the north. Therefore, the strike slip motion may be measured on faults that link marginal basins, and may not be representative of the regional kinematics of the WAM. Furthermore, Wolfenden et al. (2005) argue that the Borkenna basin did not develop in the early stages of Afar formation (see also section 4.4). But since the age of the basins is poorly constrained, early to middle Miocene age basin initiation remains a possibility. The question remains how significant the proposed first phase of deformation was since it except for Collet et al. (2000), none of the plate reconstruction efforts have felt the need to include it.

Furthermore, Chorowicz et al. (1999) predict large downfaulted crustal blocks to the east of the WAM (Fig. 8). There is however no evidence of such a structure as illustrated by the Moho depth in the area (Stab et al. 2016 and references therein, Fig. 8). Yet the effects of magmatic underplating, as reported by Mohr (1983) and Stab et al. (2016) may hide such a structure. On the other hand, the eastward dipping detachment faults should, like for the Tesfaye and Ghebreab (2013) model, account for most of the deformation and seismicity, which does not seem to be the case.

4.3.3. Westward dipping detachment model

In contrast to the models involving an eastward dipping detachment, Stab et al. (2016) propose a westward dipping detachment model. On the base of geochronological analysis (K-Ar and U-Th-Sm)/He) combined with balanced cross-sections along a NE-SW trajectory starting north of the Borkenna basin and reaching into the Afar (Fig. 8), the authors infer an initial Mio-Pliocene distributed extension followed by localized detachment faulting in the Pliocene. Numerous westward-dipping faults are interpreted to root at a mid-crustal shear zone and to accommodate significant crustal thinning. Such westward dipping detachments are also proposed by Talbot and Ghebreab (2000) based on field observations from Eritrea.

Although Stab et al. (2016) do not specifically focus on marginal graben formation and antitethic faulting, they do include them in their structural evolution scheme (Fig. 8). A “proto-marginal graben” structure would have formed during the early phase of distributed deformation. Only when rifting began localizing along the large-scale detachments rooting in the lower crust, Afar started subsiding and the WAM would have undergone flexure and antithetic faulting (Fig. 8). Magmatic underplating is needed to account for the apparent surplus of lower crust (as also stated by Mohr 1983). No further details are provided by the authors, but the concept of flexure is further explored below (section 4.4).

The Stab et al. (2016) westward detachment model could thus induce marginal flexure, accounting for marginal graben formation. However, the similarity between their large-scale extension model and the second marginal graben mechanism involving a rollover structure due to a westward detachment proposed by Morton & Black (1975, Fig. 5h) is of interest as well. The development of the marginal grabens due to a westward dipping detachment would for instance explain the apparent focus of active deformation on the eastern boundary faults. Also the possible absence of a western boundary fault at parts of the margin would fit with this model, since a detachment fault might as easily produce a rollover anticline without the formation of a compensation graben. Yet we must also stress that the Stab et al. (2016) model is more complex than the compensation graben model proposed by Morton & Black (1975), since the location of the main detachment fault with respect to the marginal graben differs in both cases (Figs. 7b, 10).

4.3.4. Flip-flop detachment model

Based on observations in the SE Afar, Geoffroy et al (2014) propose a "flip-flop tectonic" model, involving a switch from a south-westward dipping detachment to a north-eastward detachment system (Fig. 9). The authors report opposing dips in lower and upper Stratoid units that indicate a reversal of detachment direction around 2 Ma, due to a shift in mantle and magmatic activity associated with the propagation of the Gulf of Aden spreading ridge into the Afar.

This model is based on analysis in the SE of Afar, an area that is strongly affected by oblique extension due to the rotation of the Danakil Block (Souriot & Brun 1992). It is also ambiguous whether these results can or should be extrapolated to the WAM. However, if so, it may infer a relatively old marginal graben initiation on the western edge of the extensional domain, represented by minor antithetic faulting with respect to the regional detachment (Fig. 9a). Following the tectonic shift at ca. 2 Ma (Fig. 11b), the early fault became part of the new detachment system, in which the marginal grabens could have continued developing in a compensation graben form (Fig. 9c).

4.4. Marginal flexure models

In contrast to the fault-dominated mechanisms in the previous section, Abbate and Sagri (1969) suggest that the marginal basins are formed as a result of lithospheric flexure to compensate for the relative increased subsidence in Afar (Fig. 10). As specified by Kazmin et al. (1980), such a flexure would cause tensile forces and deformation would lead to antithetic faulting (Fig. 10a, b). Abbate and Sagri (1969) propose two options for the WAM. The first is a simple flexure causing antithetic faults and the formation of a marginal graben at the top of the flexure, similar to a “key stone” in an arc, adjacent to the plateau margin (Fig. 10c, c’). The second involves an additional synthetic normal fault towards Afar to account for the significant topographic drop between the Ethiopian Plateau and the Afar Depression (Fig. 10c’). Field evidence of such an additional fault has been reported (e.g. Mohr 1972; Abbate et al. 2015), yet most studies suggests that faulting is predominantly antithetic until further into the Afar rift floor and that the Afar units simply onlap on the tilted blocks (e.g. Mohr 1983; Stab et al. 2016, Fig. 4d). Also timing of fault activation and graben formation is not specified, yet it seems that a certain amount of flexural subsidence may be necessary to start brittle failure (Kazmin et al. 1980, Acocella et al. 2008, Fig. 10).

The simple flexure concept proposed by Abbate & Sagri (1969, Fig. 10c) elegantly explains the development of antithetic faults without the problems associated with large eastward detachment faults as described previously. Ongoing flexure would also explain the continued seismicity and fresh fault scarps along the antithetic marginal graben boundary faults (Gouin 1979, Illsey-Kemp et al., 2018, Fig. 2), with no need to maintain significant activity along the synthetic boundary faults.

Such marginal flexure was initially thought to be caused by outward flow of magma from large magma chambers below the sagging rift around 14 Ma direct cause for such flexure (e.g. Kazmin et al. 1980), a similar process also occurs on a smaller scale in the grabens of the central Afar (Acocella 2010). More recently however, Wolfenden et al. (2005) propose that magmatic loading can be the driving force for marginal flexure (Fig. 11a). Due to its position on a hot spot, Afar is a highly volcanic region and crustal magma injection may increase the density of the crust, which subsequently subsides. Similar magmatic loading and flexure are also reported from the SE margin of the Danakil Block (Le Gall et al. 2011, Fig. 11b) and has been numerically modeled (Corti et al. 2015b, Fig. 11c). Flexure of the WAM is suggested to be a result of focused magmatic loading along the current spreading axis in the Afar in the last magmatic stage (2 Ma-present), as deformation and associated magmatic activity are interpreted to have migrated from the rift edges towards the rift axis during three magmatic phases (Zanettin & Justin-Visentin 1975, Wolfenden et al. 2005).

This magma-loading scenario implies that the marginal grabens are of relatively young age, similar to those of the Pliocene to recent sediments found in them so far (e.g. Abbate et al. 2002; Sani et al. 2017). Still, the current apparent absence of older sediments does not exclude an older age for the marginal grabens, as such older sediments might either be covered by younger units or removed by erosion. In fact, Zanettin & Justin-Visentin (1975) and Mohr (1983) suggest flexure and marginal graben formation to have occurred early on, i.e. pre-Pliocene and probably as early as 19 Ma, which is more in line with the older magma-escape scenario.

Yet, the young basin age inferred from the magma loading scenario would be in accordance with the notion that significant flexure might be necessary to develop faults (e.g. Kazmin et al. 1980, Fig. 10a, b) and even more to develop marginal grabens. It is for instance proposed that Oligocene-early Miocene lithospheric flexure was only much later followed by marginal basin formation in Pliocene-Quaternary times (Mohr 1986). Possibly, the presence of marginal grabens is an expression of extreme flexure as a combined result of the significant uplift of the Ethiopian Plateau and the strong subsidence in the Afar. The former has been estimated to be some 2000 m, although the timing is highly debated (Corti 2009; Abbate et al. 2015 and references therein). The latter is difficult to estimate, but the decrease in crustal thickness from 40 below the Ethiopian Plateau to 25 or even 15 km in the Afar (Ebinger et al. 2010; Hammond et al. 2011) must have resulted in significant subsidence there.

Wolfenden et al. (2005) furthermore claim that deformation along the WAM, or rather in their Borkenna Basin study area, is fully controlled by magmatism and they suggest that current seismicity is due to the strong crustal thickness variations along the WAM. By contrast, Stab et al. (2016), who worked on a profile crossing the same area, invoke dominant mechanical deformation and infer magmatic underplating to fill in the gaps in the lower crust left over in their mass balances. It is therefore challenging to unify the magmatic loading effects as described by Wolfenden et al. (2005) to the westward detachment model proposed by Stab et al. (2016).

Note however that crustal flexure during rifting and passive margin formation is observed along various magmatic passive margins, and is associated with the development of thick sequences of magmatic layers, seaward-dipping reflectors (SDR), in e.g. East Greenland, Norway, the South Atlantic and the Deccan margin of India (Buck 2017; Paton et al. 2017). It would therefore be possible to study ongoing SDR formation in the Afar, as well as the underlying tectonic processes (Wolfenden et al. 2005; Corti et al. 2015b; Paton et al. 2017, and references therein).

5. Discussion

Above we presented a series of distinct mechanisms for the development of the WAM and how these fit in large-scale models for the evolution of the Afar. In Table 2 we summarize these and the associated predictions that can be tested in the field. Below we discuss the current limits to our understanding of the Afar, possible strategies for future work to exploit the full potential of the Afar, and how the current interpretations of the Afar fit in a more global perspective.

5.1. Towards a better understanding of the WAM and Afar

As discussed in the previous sections, the various options to explain widespread antithetic faulting and marginal graben formation predict wildly different structures and all have pros and cons. A major problem is that the initial observations on which these models are based are rather limited. Justin-Visentin & Zanettin (1974) and Zanettin & Justin-Visentin (1975) point out that most of the early fieldwork on the WAM was concentrated along the ca. E-W road between Dessie and Bati, since it was the only place allowing to observe a full transect of the margin and many later field campaigns have focused there as well (e.g. Chorowicz et al. 1999; Mohr et al. 1983; Stab et al. 2016). Although this particular area is easily accessible, it is a transfer zone between two marginal grabens (the Hayk and Borkenna basins, section S3 trace, Fig. 2b) and may thus not be representative for a typical WAM section (Mohr 1971; Wolfenden et al. 2005).

Other structural field studies were concentrated in Eritrea (e.g. Drury et al. 1994, Fig. 8c) and also taken as representative for the whole margin (Tesfaye & Ghebreab 2013). Next to the fact that the interpretation is contested (see section 3.3.1) and that the area is far north and may not even be considered truly part of the WAM, it is questionable whether one can simply extrapolate the observations from one section of the WAM to explain the whole margin (e.g. Mohr 1971). It is not uncommon that rift structures have significant variations along strike and the WAM is already known to have a different topographic profile, lithology, crustal thickness and rift initiation age from north to south, as well as a different strike in its southernmost sector (see section 2). Furthermore, Zanettin and Justin-Visentin (1975) note the possibility that the typical antithetic faulting of the WAM may be due to superficial basement-controlled deformation in the massive Trap basalts; where the latter are eroded and the basement is exposed (mostly in the northern part of the WAM), a simpler geology with less defined structures seems to dominate (Fig. 2a). Analogue experiments may shed more light on this topic (e.g. Holland et al. 2006; Kettermann et al. 2018).

Furthermore, the complex tectonics of the Afar, including the rotation of the Danakil Block leading to the formation of the current Danakil conjugate margin instead of the older Yemen margin, as well as the late opening of the Main Ethiopian Rift to the south, probably caused quite significant structural variations from north to south. Any comprehensive explanation for the development of the WAM and its links to the regional tectonic evolution should account for that. Yet a margin-wide structural interpretation on which such a model could be based is lacking at the moment. We therefore recommend a thorough structural assessment of the WAM, in order to determine which faults are dominant and what their orientations are, to characterize the marginal basin size and geometries. Here, geomorphological analysis may help to determine (relative) ages of fault activity and earthquake analysis could help to determine current fault activity (e.g. Illsley-Kemp et al. 2018). An additional objective should be to obtain reflection seismic sections calibrated by borehole data along the WAM, which would provide invaluable data to constrain fault geometries and slip histories in depth, the results of which could subsequently be compared to the structures interpreted on seismic data from mature passive margins.

Other important information that is currently poorly constrained concerns the age and thickness of the sediments in the marginal grabens, as well as the architecture of the basin infill. The oldest known units are of Pliocene age and there may be up to 550 m of sedimentary infill (Sani et al. 2017), but no well logs or reflection seismic data are available to verify if there are yet older units or deeper depocenters and how the sediments relate to the faults. The age of the marginal grabens, their structural architecture and their tectono-sedimentary features, which may be keys to determine which model for the WAM is correct, thus remain obscure.

A further question is the amount of deformation needed to generate antithetic faulting and/or a marginal graben, i.e. how much stretching for the detachment models and/or how much (relative) subsidence in case of marginal flexure. In this context, it would also be useful to not only determine the subsidence the Afar has undergone, but also the significant uplift of the rift shoulder (the Ethiopian Plateau) and whether these vertical motions occurred in one event or in steps. The latter remains highly debated (Abbate et al. 2015 and references therein).

The uncertainties surrounding the geological history of the WAM provides interesting opportunities for future laboratory experiments or numerical simulations. Few studies formally model the dependence of rift evolution on rheology and structure of the lithosphere, but instead present conceptual models that attempt to reconcile with geophysical and structural data. Future work may for instance assess the influences of lithospheric rheology, such as pre-existing (Pan-African) tectonic weaknesses, the presence and thickness of a ductile lower crust, the amount of brittle-ductile coupling, but also of surface processes and magmatism on margin development. These parameters are known to influence rift systems (e.g. Brun et al. 1999; Corti et al. 2003, 2004; Hardy et al. 2018; Burov & Cloetingh 1997; Burov & Poliakov 2001; Zwaan et al. submitted) and by running such models, it would be possible to get an impression of the relative importance of the various factors may have affected the WAM at various stages of its evolution.

5.2. Comparison with models for global rift and passive margin evolution

Since Afar provides a unique opportunity to study continental break-up processes, it is important to reflect on how the area may compare to generalized end member models of rifting. Here we link the various rift models for Afar to either the classical pure shear model in which lithospheric stretching is accommodated symmetrically by viscous deformation (e.g. McKenzie 1978, Fig. 12a), asymmetric simple shear models involving a lithospheric-scale detachment fault (e.g. Wernicke 1985, Fig. 12b), and the magma-controlled rifting model in which magmatic processes and diking account for the observed extension in a rift system (e.g. Buck 2004, 2006). Since most authors do not specifically link their models for the WAM to lithospheric-scale processes, we also produce a proper classification (Table 2), combined with a summarizing overview of the rift modes reported in the Afar region (Fig. 12d).

Pure shear

The erosion model by Mohr (1962) (Fig. 5a-d) and the block rotation model (Fig. 5f), link best to pure shear stretching, as only high-angle normal faults are implied. The mechanical marginal flexure favoring the presence of only high angle normal faults is also consistent with the pure shear model (Abbate & Sagri 1969, Fig. 10). In this case, the relatively little crustal thinning occurs beneath the WAM, and maximum crustal thinning develops beneath the central rift axis in Afar. Also in the Main Ethiopian Rift to the south, which is not yet as developed as the Afar Depression, the geometry and location of upper crustal faults and of crustal thinning with respect to the surface expression of rifting is more compatible with an initially pure shear model (e.g. Corti 2009; 2012, and references therein, Fig. 12d). A continuation of this system into Afar would be consistent with the northward increasing rift evolution trend, including increasing magmatism, as observed in the Main Ethiopian rift (e.g. Agostini et al. 2011, Fig. 12d).

Simple shear

The detachment models for the WAM involve a simple-shear mode of crustal extension, a type of lithospheric thinning that accounts for the many large-scale detachment structures typical for passive margins (e.g. Lister et al. 1986; Peron-Pinvidic et al. 2013). This is counter to observations from early stages of rifting in the East African rift (including the Main Ethiopian Rift) where evidence for large scale detachment faults is lacking, and a pure shear model of rifting (with the addition of magma in some regions) seems more likely. A simple solution is that continental rifting may initiate as pure shear, but evolve to simple shear later in the break-up process (Manatschal 2004, Lavier & Manatschal 2006).

Stab et al. (2016), adopt a similar scenario and include an initial phase of pure shear rifting followed by a later phase of simple shear detachment faulting in their structural evolution of Afar (Fig. 8). Such a shift from distributed to localized deformation ultimately leads to continental break-up and mantle exhumation (Manatschal 2004, Lavier & Manatschal 2006) and has been interpreted as applicable for breakup in the Gulf of Aden (Bellahsen et al. 2013). By contrast, both pure shear and simple shear models have been proposed for the less mature Red Sea basin (Ghebreab 1998 and references therein). The notion that we may currently observe different modes of rifting in both Afar and the Red Sea (Fig. 12d), as expressed by the various contrasting tectonic models proposed for the area (Ghebreab 1998; Table 2), may indicate that (parts of) the Afar region is currently undergoing a transition from pure shear to simple shear rifting. The Afar region could thus provide a perfect natural laboratory to study such shifts of rift style.

Magma-controlled rifting

Both the pure shear and simple shear rift models ignore the effects of magmatism on lithospheric thinning, a factor that is key to the magmatic loading model (Wolfenden et al. 2005). In Afar, lower crustal intrusions have facilitated extension with less crustal thinning than expected from the amount of horizontal extension (Mohr 1983; Stab 2016) and current deformation in the upper crust is thought by many to largely occur by means of episodic dike intrusion along magmatic segments in Afar (e.g. Hayward & Ebinger 1996; Ebinger & Casey 2001; Wright et al., 2006). However, pure magma-controlled rifting (Fig. 12c) does not explain the presence of km-offset faults at the rift margins, the protracted breakup history and resultant large width of continent to ocean transition in Afar, nor the significant crustal thinning we observe. It therefore is more likely that extension by magma intrusion occurs within a framework of mechanical rift evolution (e.g. Beutel et al. 2010), which we refer to as “magma-assisted rifting”. Instead of experiencing a shift from pure shear to simple shear, such magma-assisted rifting may allow break-up within a pure shear system (Ebinger 2005), thus avoiding the shift from pure to simple shear rifting that may be typical for magma-poor systems (Reston 2009).

Pathways to continental break-up

The above discussion leads to the idea that the various rifting modes observed in the Afar region possibly reflect different steps on different pathways towards continental break-up, as summarized in Fig. 13d. We infer that rifting may initiate as a pure shear-dominated system. As the rift evolves, significant magmatism can localize deformation along axial spreading centers within a pure shear context. However, when magmatic influences are minor or absent, we can expect a mechanical control on rifting and a shift from a pure to a simple shear rifting mode. If extension persists, both pathways would eventually lead to strong localization of deformation and continental break-up and the formation of either magma-rich or magma-poor passive margins. These proposed sequences are end members based on data from the Afar region, but they may provide a relevant framework for the interpretation of rifts and rifted margins worldwide.

6. Conclusion

The Afar region represents a unique tectonic setting, allowing the study of ongoing rift development and various stages of continental break-up. In this paper we present an overview of the geological and geomorphological characteristics of the Western Afar Margin (WAM) and the various scenarios that have been previously proposed for its evolution. The margin is characterized by a steep decline in topography and crustal thickness from the Ethiopian Plateau into the Afar Depression, as well as a series of marginal grabens and a general presence of antithetic faulting. Although rifting is shifting to the rift axis, significant deformation is still occurring along the margin.

Models for the evolution of the WAM involve either isostatic loading effects due to erosion, rift-induced block rotation, large-scale detachment fault development or crustal flexure due to lithospheric stretching or magmatic loading. This wide variation of potential mechanisms for WAM development may reflect a general structural variation along the margin and in Afar, involving different stages of rift formation and possibly indicating two distinct pathways leading to continental break-up.

Yet we must stress that in order to better understand the system and to fully exploit the research potential of the region, further assessment of the WAM and its relation to the Afar will be necessary. Important questions are for instance which boundary faults are active and what the full stratigraphy and their structural architecture in the marginal basins is. Reflection seismic and well data would be of great help, but more practical approaches could include earthquake analysis and fieldwork, as well as analogue and numerical modeling. The findings of such future work, combined with data from rifts and passive margins from around the globe will be of great importance to improve our understanding of the processes involved in continental breakup and to better constrain the sequence of events leading from initial rifting to oceanic spreading.

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Tables

Basin name (Abbate et al. 2015)	Alternative basin name(s)	Source alternative name
-	Damas *	Tesfaye & Ghebreab (2013)
Buia**	Massawa-Buia	Sani et al. (2017)
Garsat	Maglala-Renda-Coma	Mohr (1967), Tesfaye & Ghebreab (2013)
Teru	Dergheha-Sheket	Mohr (1967), Tesfaye & Ghebreab (2013)
-	Abala	This paper
Kobo	Guf Guf	Mohr (1967), Tesfaye & Ghebreab (2013)
	Azebu Gallo (northern part)	Mohr (1967)
	Kobbo (southern part)	Mohr (1967)
Hayk***	Menebay-Hayk	Mohr (1967), Tesfaye & Ghebreab (2013)
Borkenna		
-	Robi	Mohr (1967), Gouin (1979)

Table 1. Overview of terminology applied to the fault-bounded basins along the WAM, for locations see Figs. 1 and 2.

* The Damas Basin does not align the WAM (Figs. 1 and 2), but is considered a marginal graben by Tesfaye & Ghebreab (2013)

** The Buia Basin forms the continuation of the Danakil rift axis and may therefore not be considered a true marginal graben (Fig 2).

*** The name “Hayk basin” is poorly chosen, as the city of Mesra and not the city (or lake) of Hayk are situated in the main regional depocenter (Mesra plain, Fig. 2). Also, the basin extent is poorly constrained in previous works, since the Mesra plain only forms a small part of amuch larger sigmoidal graben structure that cuts into the Ethiopian plateau Stab et al. (2016, Fig. 2). Yet for reasons of consistency with previous literature, we maintain the term “Hayk basin” and use it to refer to this large graben structure.

<table>
<tr><th colspan="2">Deformation mechanism</th><th>Potential model for the evolution of Afar</th><th>Rift mode</th><th>Marginal graben initiation</th><th>Dominant marginal graben boundary fault</th></tr>
<tr><td colspan="2">A. Erosion
(Mohr 1962, Fig. 5a-d)</td><td>Extension/rifting→ rift shoulder erosion
(Mohr 1962, Fig. 5a-d)</td><td>?</td><td>Late Miocene?</td><td>Both?</td></tr>
<tr><td colspan="2">B. Block rotation
(Black et al. 1972; Kazmin et al. 1980; Zannetin & Justin-Visentin 1975, Fig. 6e-f)</td><td>Lower crustal creep due to (symmetric?) tectonic extension (Black et al. 1972, Fig. 6e-f)</td><td>Pure shear?
(Fig. 12a)</td><td>?</td><td>Eastern boundary fault</td></tr>
<tr><td rowspan="4">C. Detachment fault</td><td rowspan="3">C1. Eastward dipping detachment fault
(e.g. Morton & Black 1975, Fig. 5g)</td><td>Initial eastward dipping detachment followed by distributed extension (Tesfaye & Ghebreab 2013, Fig. 6)</td><td>Simple shear
(Fig. 12b)</td><td>“old” (start of extension):
ca. 25 Ma</td><td>Western boundary fault</td></tr>
<tr><td>Strike-slip followed by an eastward dipping detachments due to gravitational collapse (Chorowicz et al. 1999, Fig. 7)</td><td>Simple shear
(Fig. 12b)</td><td>Strike-slip (phase 1): Miocene
Phase 2 (collapse): Pliocene-Quaternary</td><td>Western boundary fault</td></tr>
<tr><td>Flip-flop tectonics: minor initial eastward faulting followed by major eastward detachment (Geoffroy et al. 2014, Fig. 9)</td><td>Simple shear
(Fig. 12b)</td><td>?</td><td>Western boundary fault</td></tr>
<tr><td>C2. Westward dipping detachment fault
(Morton & Black 1975, Fig. 7h)</td><td>Distributed extension followed by westward dipping detachments (Stab et al. 2016, Fig. 9)</td><td>Pure shear, followed by simple shear
(Figs. 10, 12)</td><td>“young”:
Pliocene, ca. 5 Ma</td><td>?</td></tr>
<tr><td colspan="2" rowspan="4">D. Marginal flexure
(Abbate & Sagri 1969, Fig. 10)</td><td>Marginal flexure with eastward dipping fault between the WAM and Afar (Abbate & Sagri 1969, Fig. 10c’)</td><td>Pure shear
(Fig. 12a)</td><td>?</td><td>Eastern boundary fault</td></tr>
<tr><td>Early marginal flexure (Zanettin & Justin-Visentin 1975; Mohr 1983)</td><td>Pure shear
(Fig. 12a)</td><td>“old” pre-Pliocene
(Mohr 1983)</td><td>Eastern boundary fault?</td></tr>
<tr><td>Magmatic loading and progressive migration of deformation to rift axis (Wolfenden et al. 2005, Fig. 11)</td><td>Pure shear
(Fig. 12a)</td><td>“young” (after shift to rift axis):ca. 2 Ma</td><td>Eastern boundary fault</td></tr>
<tr><td>Distributed extension followed by westward dipping detachments and flexural rollover (Stab et al. 2016, Fig. 8)</td><td>Pure shear
(Fig. 12a)</td><td>“young”:
Pliocene, ca. 5 Ma</td><td>Eastern boundary fault</td></tr>
</table>

Table 2. Overview of mechanisms for the formation of the WAM structural architecture with associated models for the evolution of the Afar and the associated crustal extension mode, as well as predictions that can be tested in the field.

Images

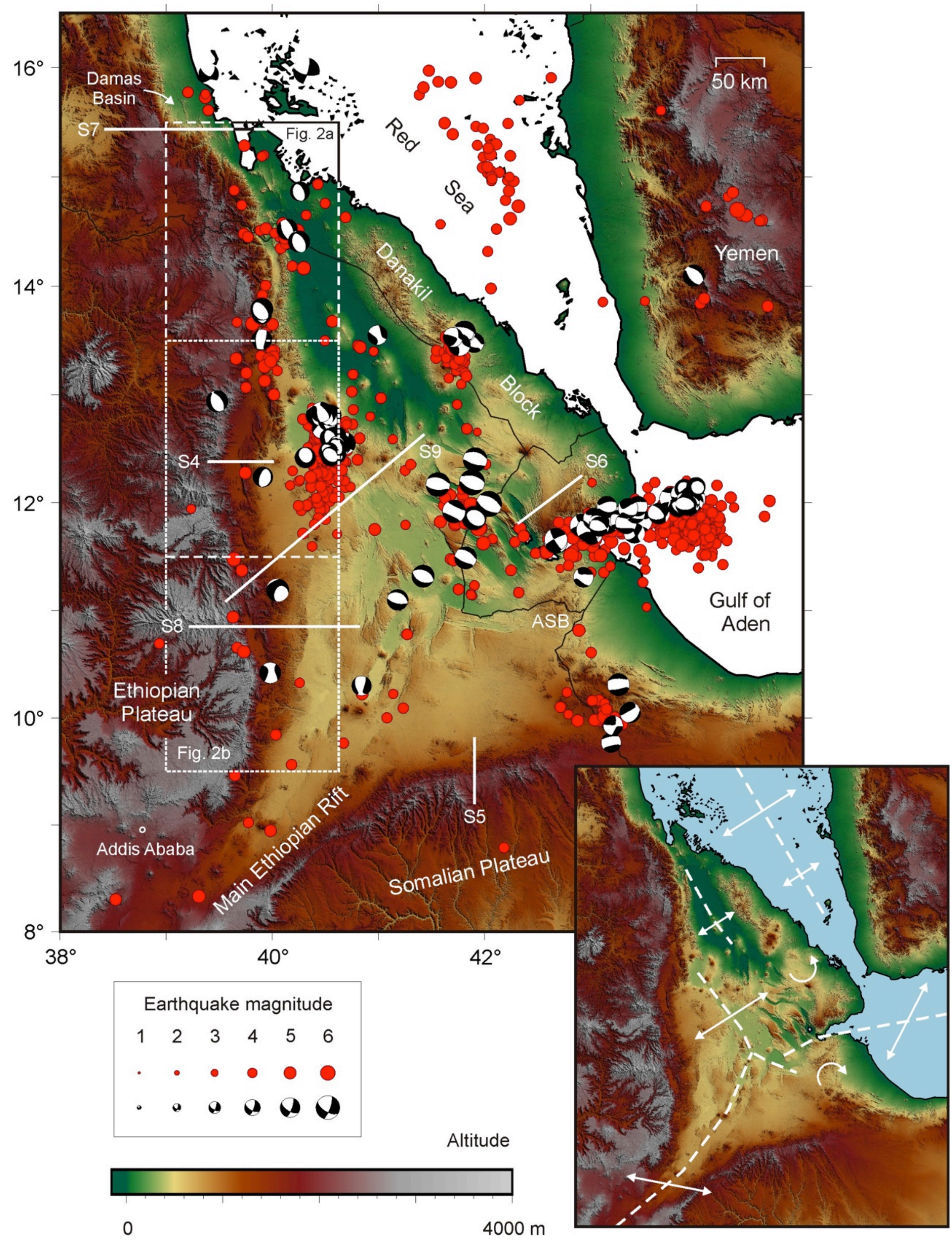

Fig. 1. Afar Depression in East Africa and the location of the Western Afar Margin (WAM). Red dots indicate historic earthquakes from the 1973-2018 NEIC earthquake catalogue. White lines indicate geological sections. Focal mechanisms are derived from the GCMT catalogue (Dziewonski et al. 1981; Ekström et al. 2012). Inset shows spreading directions (McClusky et al. 2010; ArRahjehdi et al. 2010; Saria et al. 2014;). ASB: Ali-Sabieh/Aïsha Block.Topography is derived from ASTER data (30 m resolution).ASTER GDEM is a product of NASA and METI.

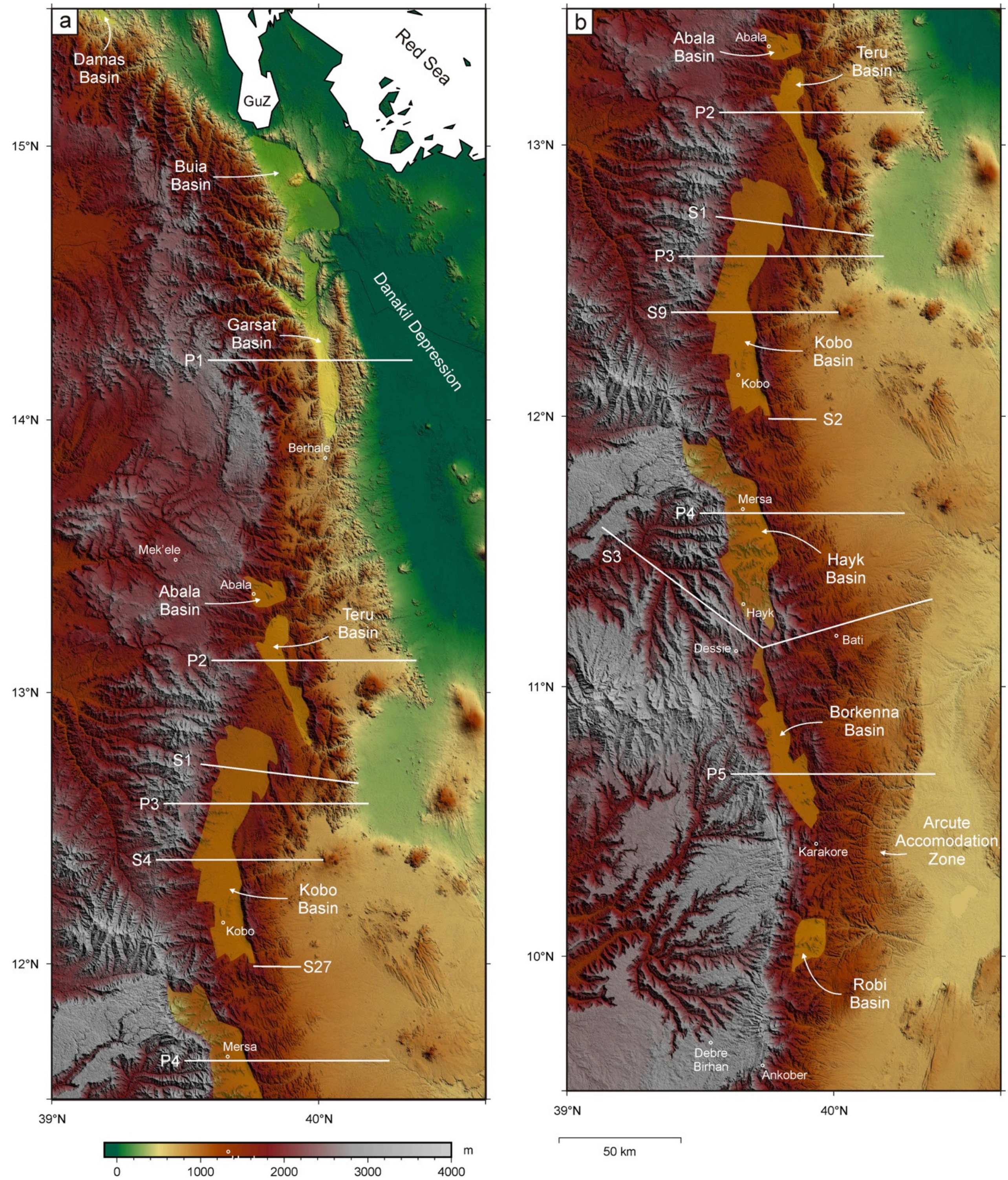

Fig. 2. Overview of basin locations along the Western Afar Margin (WAM). Transparent yellow polygons indicate the extents of the marginal grabens. White lines follow the traces of topographic profiles P1-5 and geological sections (S1-3, 9) as presented in Figs. 3 and 4. Note that the location of section S2 is poorly constrained. For locations of (a) and (b) see Fig. 1. GuZ: Gulf of Zula. Background topography is derived from ASTER data (30 m resolution). ASTER GDEM is a product of NASA and METI.

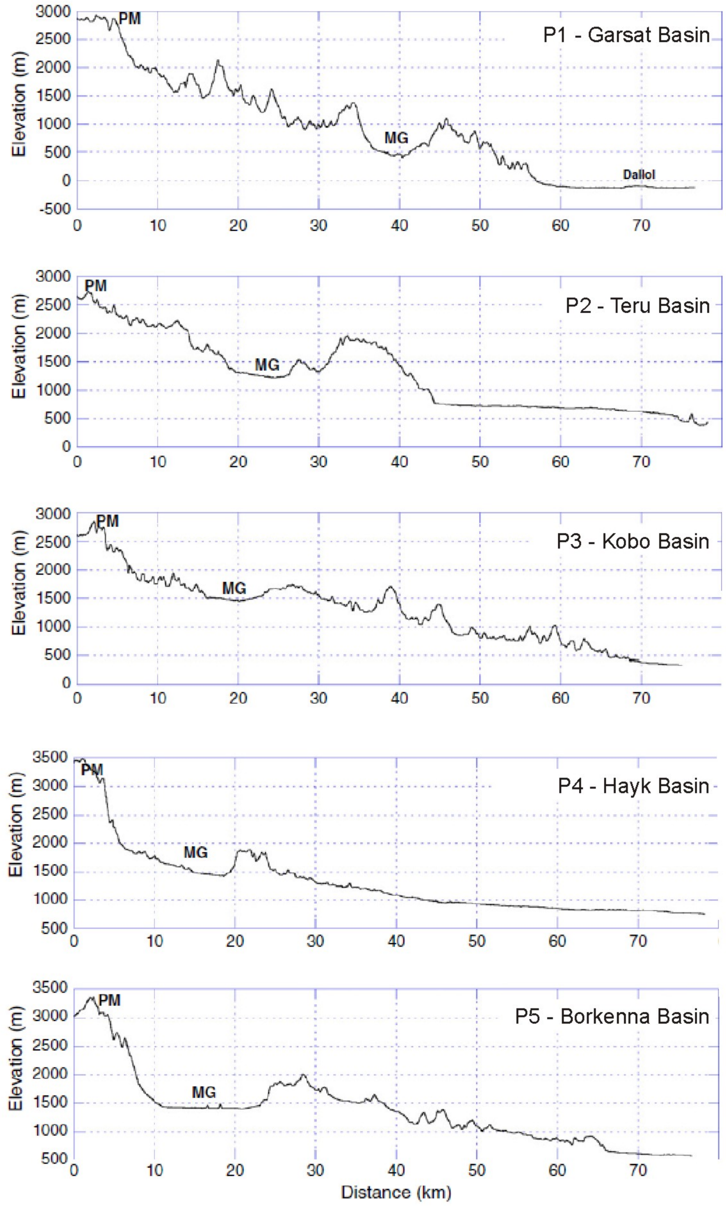

Fig. 3. Topographic profiles of the various basins along the WAM. PM: plateau margin, MG: Marginal graben. For locations see Fig. 2. Modified after Tesfaye and Ghebreab (2013).

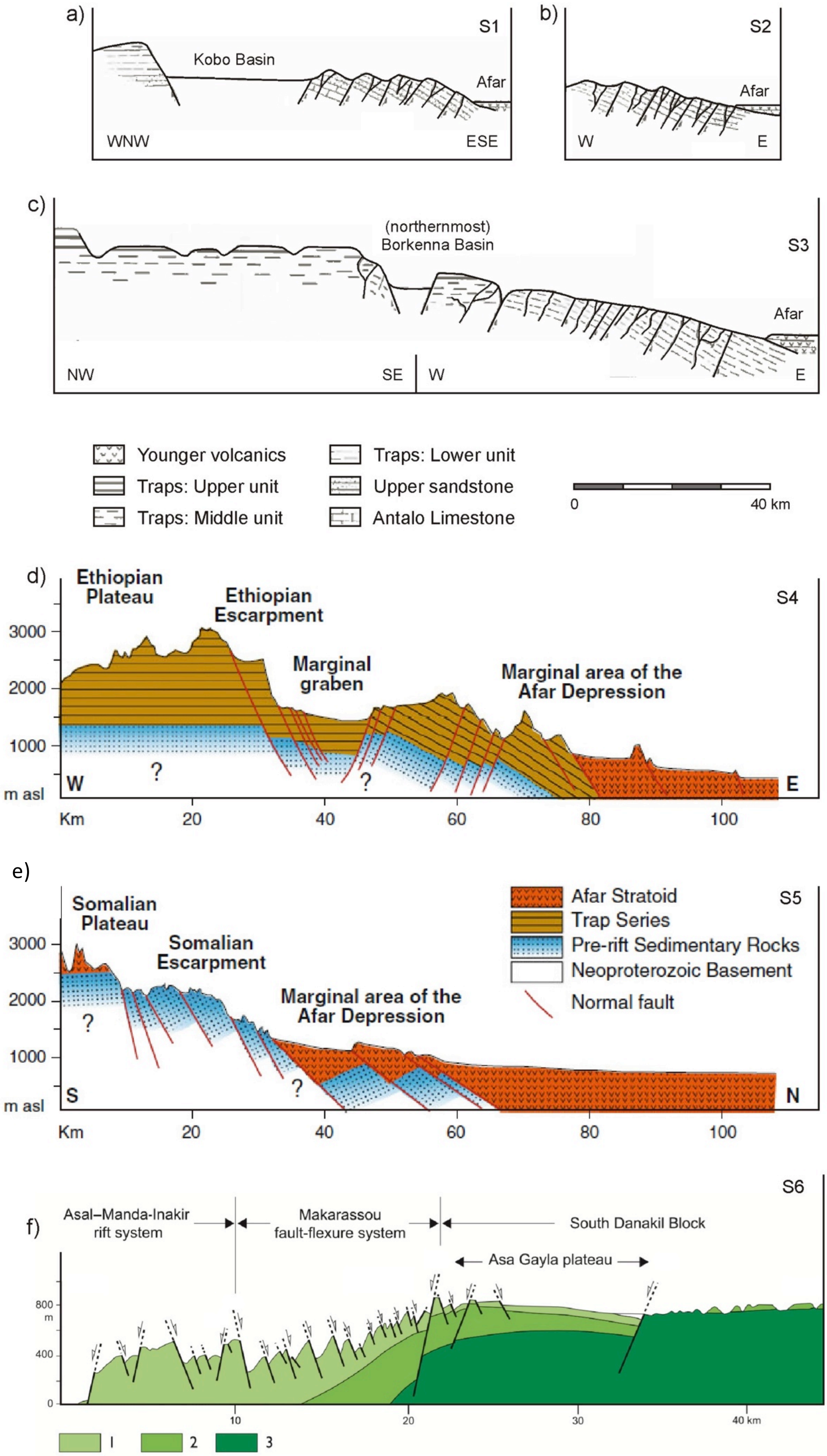
a)
S1
Kobo Basin
Afar
WNW
ESE
b)
S2
Afar
W
E
c)
(northernmost)
Borkenna Basin
S3
Afar
NW
SE
W
E
Younger volcanics
Traps: Upper unit
Traps: Middle unit
Traps: Lower unit
Upper sandstone
Antalo Limestone
0
40 km
d)
Ethiopian Plateau
Ethiopian Escarpment
Marginal graben
Marginal area of the Afar Depression
S4
3000
2000
1000
m asl
W
E
?
Km
20
40
60
80
100
e)
Somalian Plateau
Somalian Escarpment
Marginal area of the Afar Depression
Afar Stratoid
Trap Series
Pre-rift Sedimentary Rocks
Neoproterozoic Basement
Normal fault
S5
3000
2000
1000
m asl
S
N
?
Km
20
40
60
80
100
f)
S6
Asal–Manda-Inakir rift system
Makarassou fault-flexure system
South Danakil Block
Asa Gayla plateau
800 m
400
0
10
20
30
40 km
1
2
3

Fig. 4. Interpreted geological sections through the margins of the Afar. (a) Section S1 in the northern Kobo basin, near Corbetta. (b) Section S2 in the transfer zone between the Kobo and Hayk basins, near Weldiya. (c) Section S3 at the northern end of the Borkenna Basin, near Dessiè. Modified after Abbate & Sagri (1969). (d) Section S4 through the Kobo Basin. Modified after Beyene & Abdelsalam (2005) and Corti et al. (2015a). (e) Section S5 through the Somalian margin near Dire Dawa, showing the typical synthetic faulting style. Modified after Beyene & Abdelsalam (2005) and Corti et al. (2015a). (f) Section S6 near the southern tip of the Danakil Block. 1 and 2: S_1 and S_2 Stratoid basalts, respectively, 3: Dalha basalts. Modified after Le Gall et al. (2011). For section locations see Figs. 1 and 2.

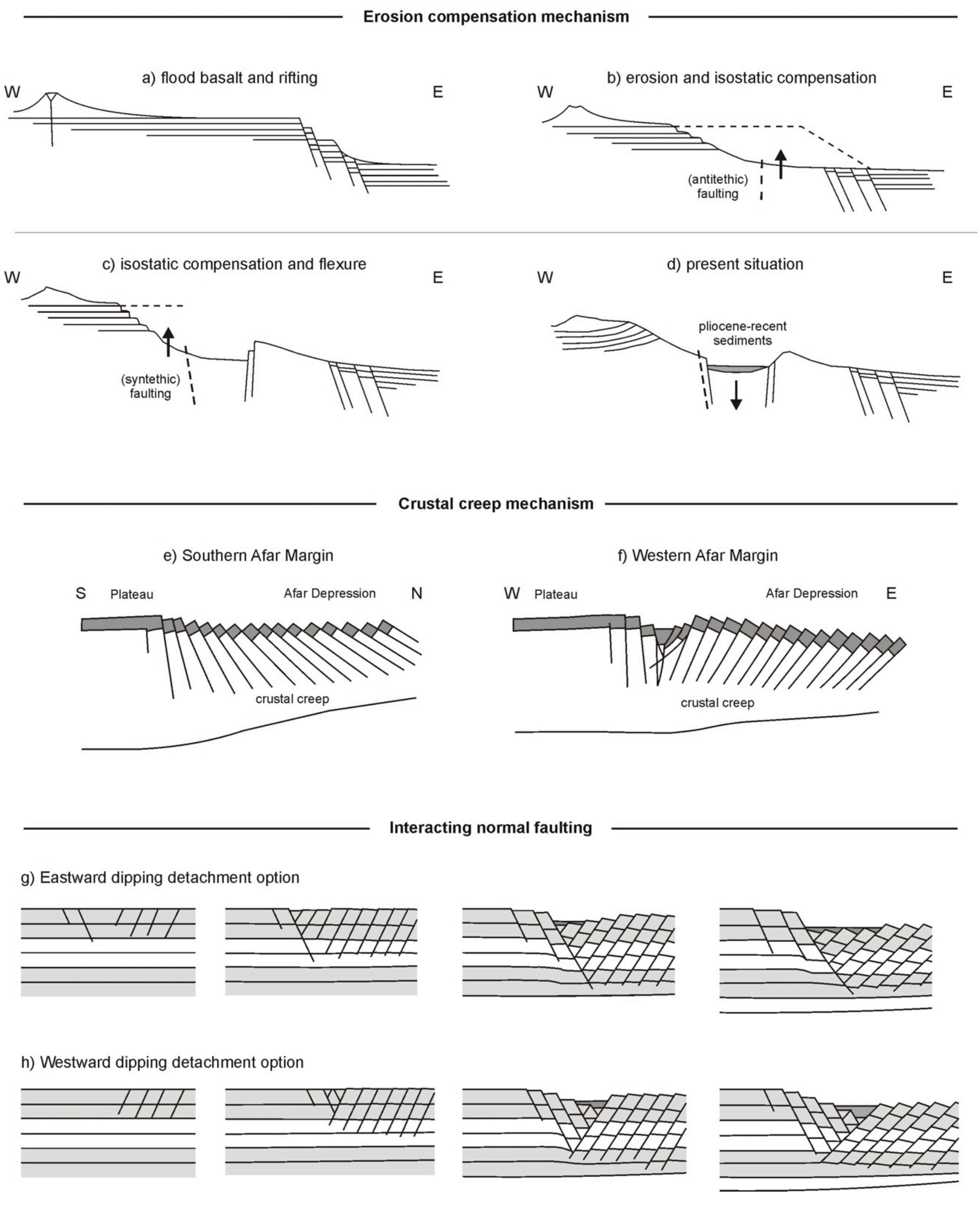

Fig. 5. Potential mechanisms for the formation of the WAM structural architecture. (a-d) Erosion compensation model as proposed by Mohr (1962). (a) Main Miocene “ post-trap” rifting. (b) Denudation causes lithospheric strain and fracturing along A-A’ (as in the present Kobo Basin). (c) Further readjustment induces faulting along B-B’. (d) Final structure. Image redrawn after Mohr (1962). (e-f) Schematic sections depicting crustal structures along the margins of the Afar, interpreted as a result of crustal creep (a) near Dire Dawa (Southern Afar Margin, SAM, analogue to S5, Fig. 4e) and (b) in the region of Maychew (WAM, analogue to S4, Fig. 4d). The transition from synthetic to antithetic faulting could have been caused by massive block rotation. Redrawn after Black et al (1972). (g-h) Models of marginal graben formation due to the interaction of synthetic and antithetic faults along the developing WAM. (a) Situation involving a dominant eastward (synthetic) fault and (b) a dominant westward (antithetic) fault. Redrawn after Morton and Black (1975).

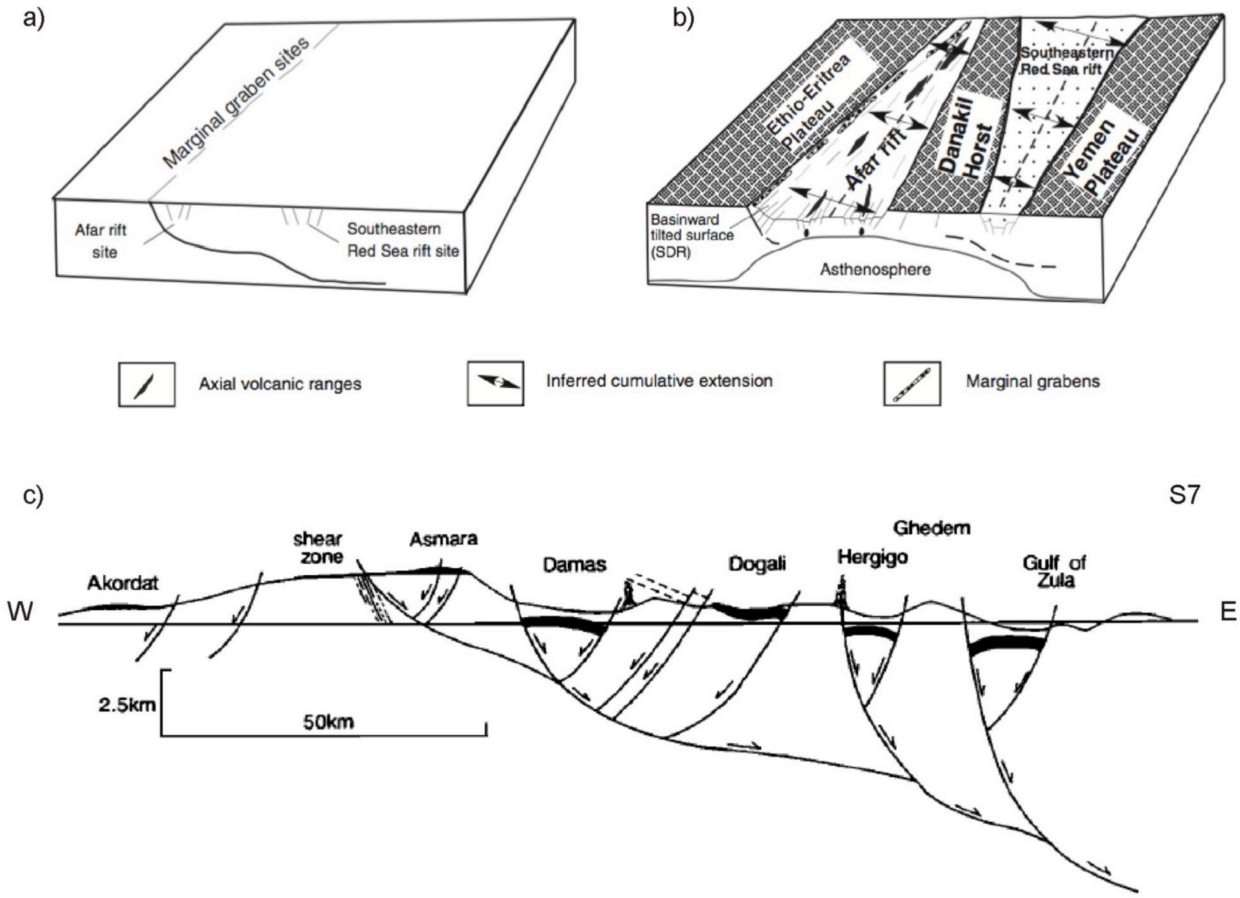

Fig. 6. (a-b) Development of the Afar according to Tesfaye and Ghebreab (2013), involving an initial detachment fault dominated system, followed by a phase of more distributed extension. (c) Interpreted section S7showing an eastward dipping detachment in the Damas area (northernmost WAM), for location of section see Fig. 2a. Modified after Drury et al. (1994) and Tesfaye and Ghebreab (2013).

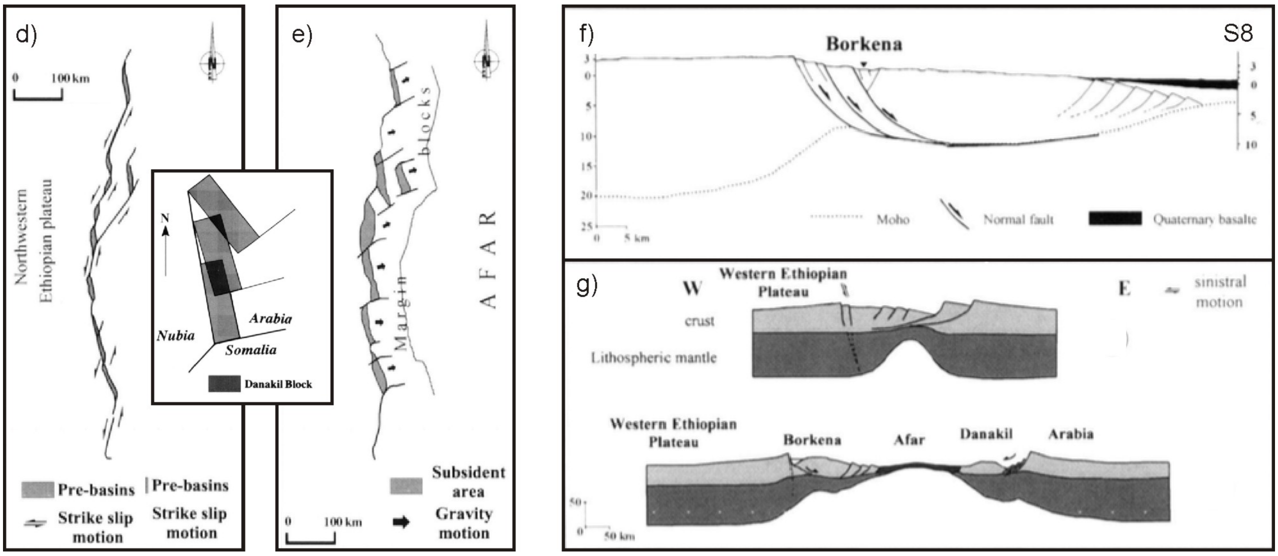

Fig. 7. Evolution of the WAM and its marginal grabens according to Chorowicz et al. (1999). (a) Sinistral strike-slip phase (early to middle Miocene) and (b) gravitational collapse, both in map view. Inset between (a) and (b): schematic map view of the translation and rotation of the Danakil Block. (c) Interpreted section S8 through the Borkenna basin with an eastward dipping detachment system. For section location see Fig. 1. (d) Schematic section view depicting the evolution of the lithosphere and the marginal grabens during the first and last phases of WAM development. Image modified with permission from the Swiss Geological Society.

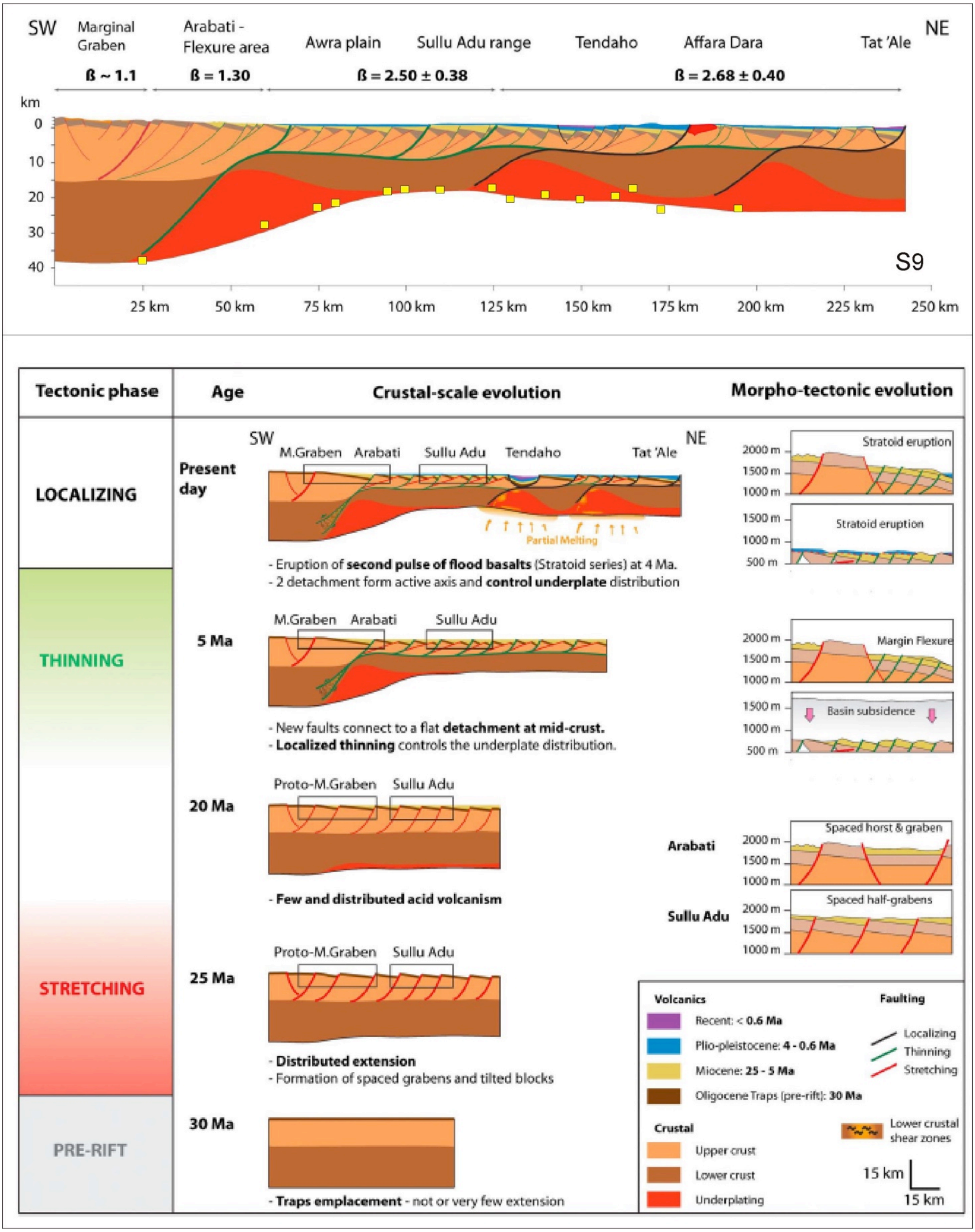

Fig. 8. Interpretation of section S9 trough the WAM (above) and Afar, as well as its interpreted structural evolution (below). Yellow squares indicate receiver function Moho depth after Hammond et al. (2011) and Reed et al. (2014). For section location see Fig. 1. Image modified after Stab et al. (2016).

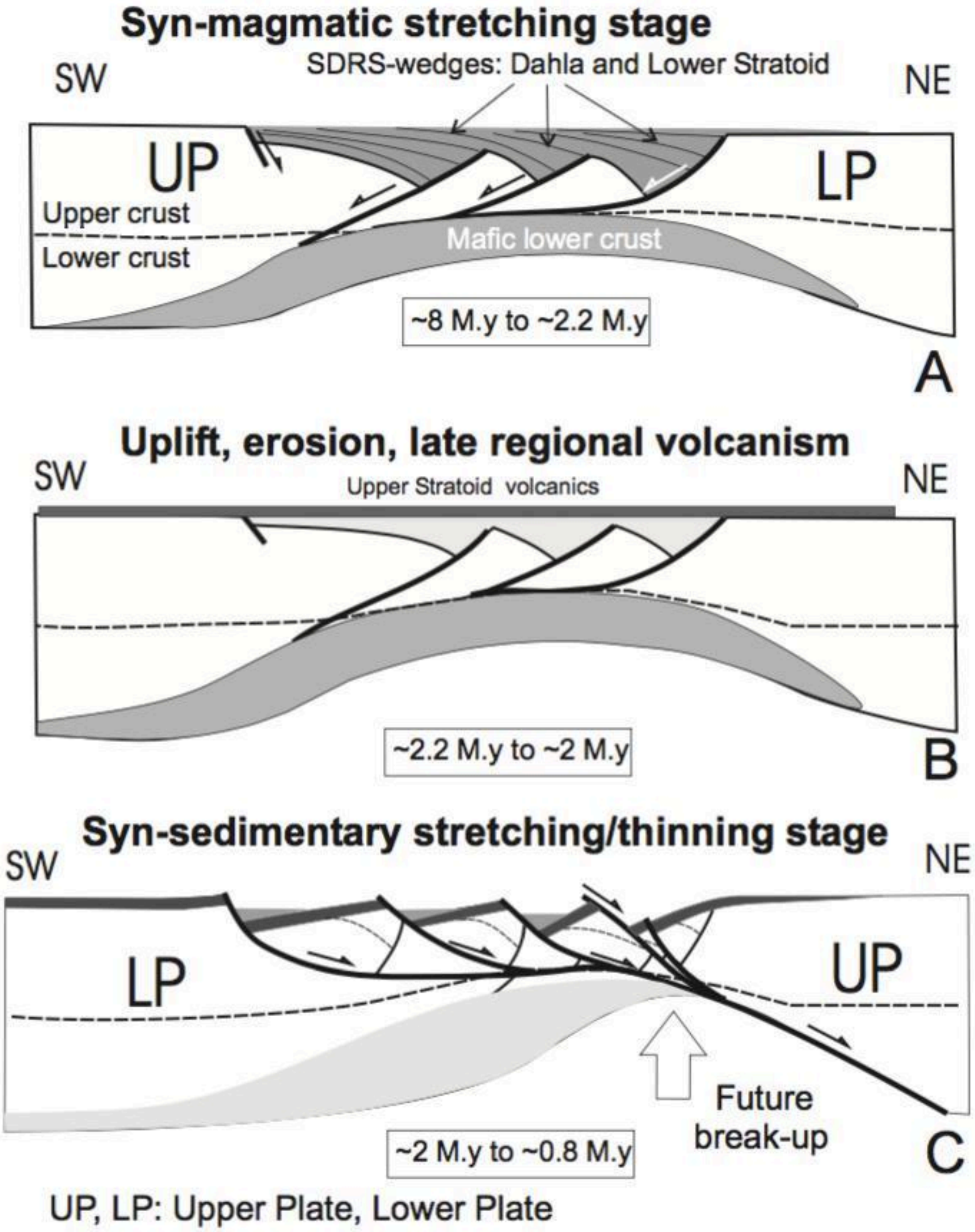

Fig 9. Flip-flop tectonic model for the SE Afar over the last 9 Ma as proposed by Geoffroy et al (2014). (**a**) Volcanic margin stage coeval with extrusion of Dahla–Lower Stratoid Series, and mafic underplating. (b) Transitional phase involving uplift, erosion and extrusion of the Upper Stratoid Series. (c) Pre-breakup detachment-type tectonics. The early structures shown in (a) are only partly indicated. Image modified after Geoffroy et al. (2014).

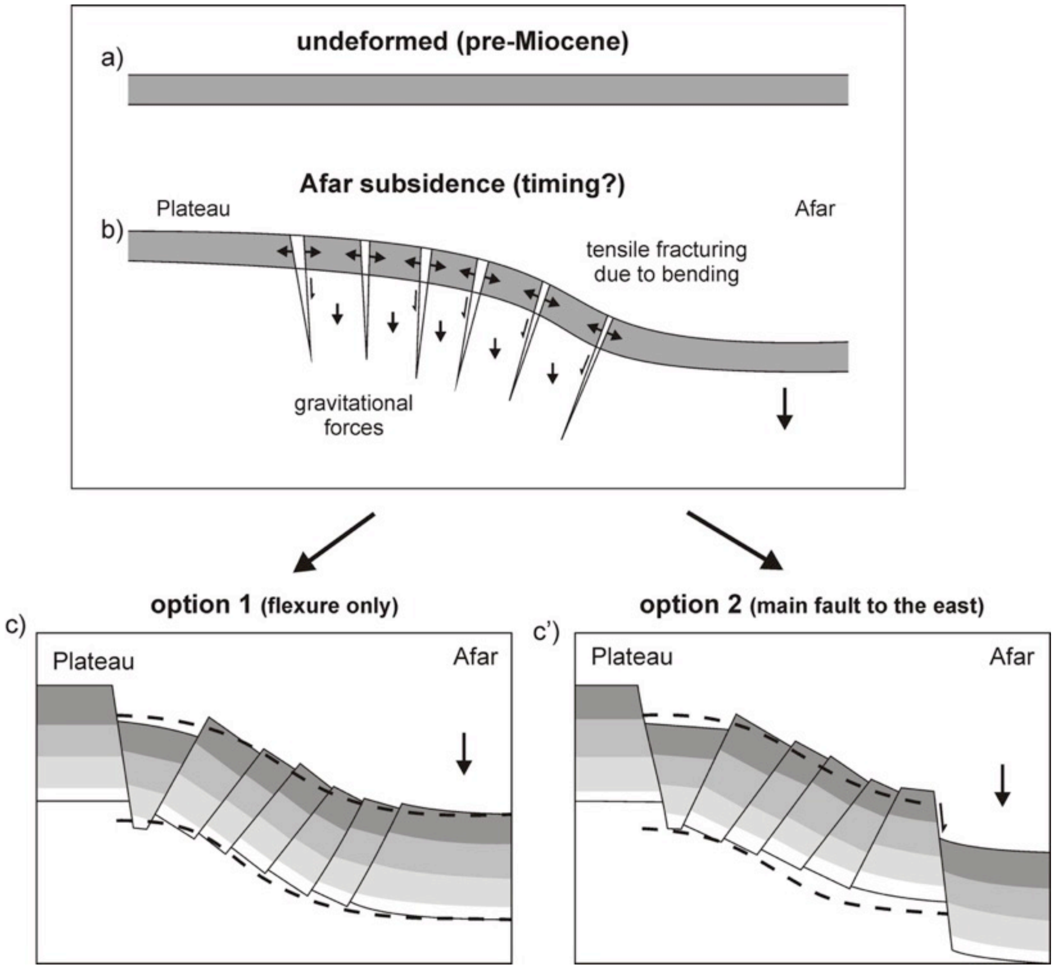

Fig. 10. (a-b) Development of antithetic faults due to flexure (Kazmin et al. 1980). (c, c') two types of flexure proposed for the WAM by Abbate and Sagri (1969). (c) depicts a simple monocline with the marginal graben acting as a keystone, (c') shows the same structure, with and additional synthetic fault between the WAM and the Afar.

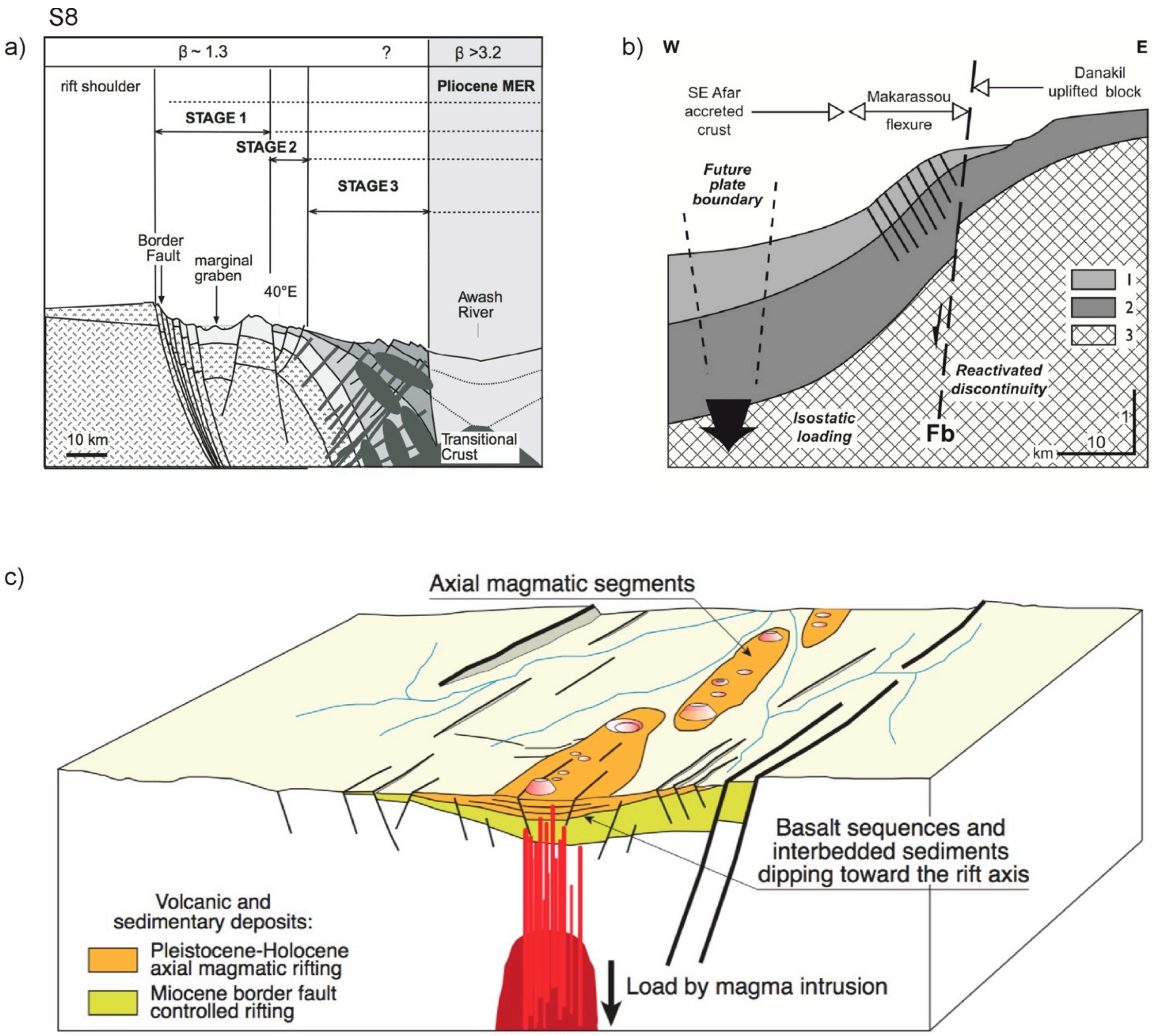

Fig. 11. Examples of magmatic loading and resulting crustal flexure as interpreted in the Afar and Main Ethiopian Rift. (a) Section S8 at 10˚50'N in the Borkenna Basin area (Modified after Wolfenden et al. 2005). (c) Situation at the southern tip of the Danakil Blok in the east of the Afar. 1. Stratoid basalts (3–1 Ma); 2. Dalha basalts (8–4 Ma); 3. Volcanic substratum (>8 Ma). Modified after Le Gall et al. 2011, see also section S6 in Fig. 4f. (c) Flexure developing in the Main Ethiopian Rift, where initial deposition processes are controlled by the rift boundary faults. In a later phase, magma intrusion along the rift axis results in progressive tilting of volcanic and sedimentary strata (Modified after Corti et al. 2015b). For section locations see Fig. 1.

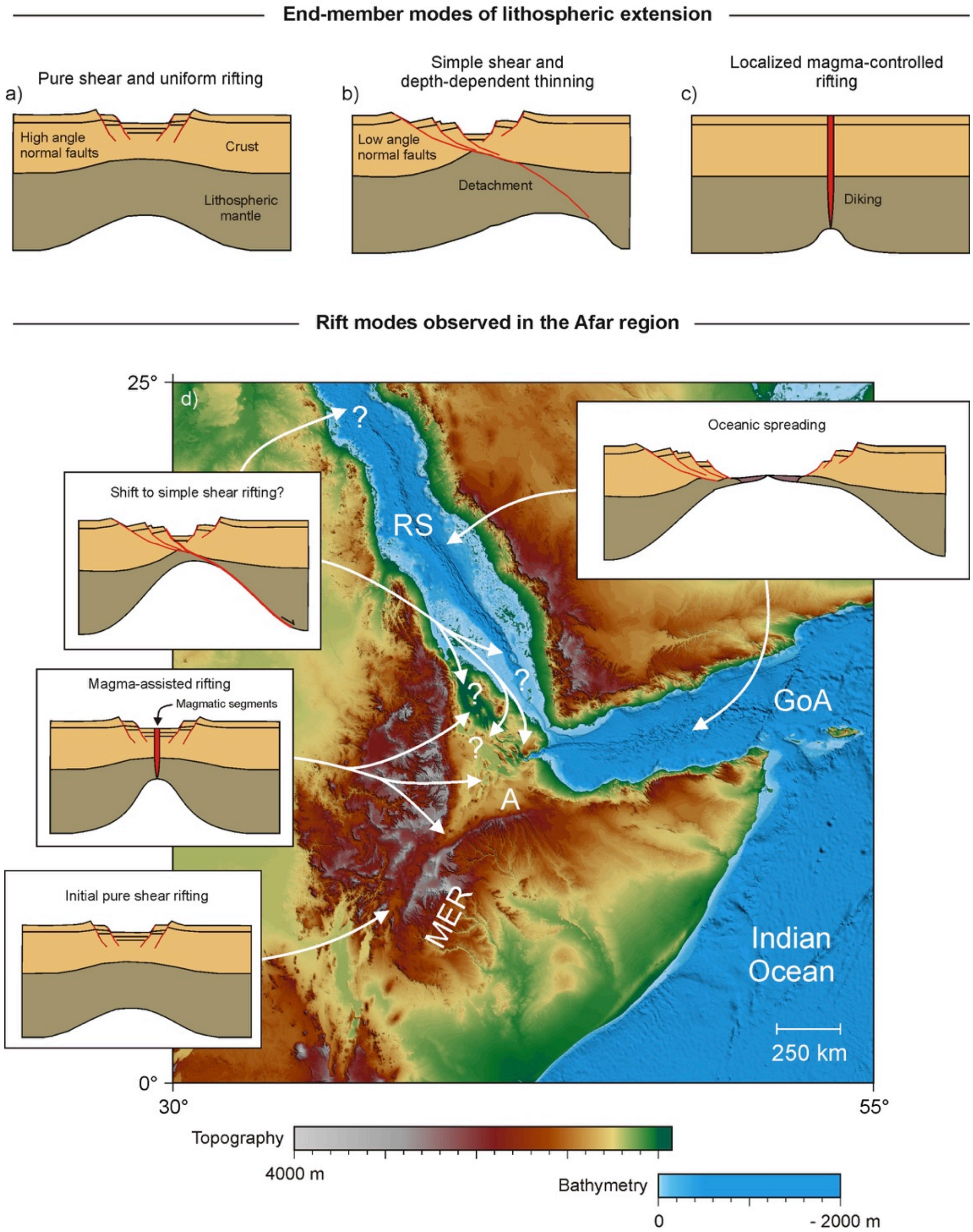

Fig. 12. Schematic overview of (a-c) end-member modes of lithospheric extension as well as (d) rift modes occurring in the Afar region. (a) Pure shear involving symmetric stretching (e.g. McKenzie 1978). (b) Simple shear via a large-scale detachment fault (e.g. Wernicke 1985). (c) Magma-controlled rifting (e.g. Buck 2004, 2006). (d) Distribution of modes in the Afar region. Pure shear rifting occurs in the southern Main Ethiopian Rift (MER), magma-assisted pure shear rifting is dominant in the northern MER and southern Afar (A), and probably active in the Danakil Depression (northern Afar) as well. In the Central Afar, parts of the Red Sea (RS) and the propagating tip of the Gulf of Aden (GoA), a shift from pure to simple shear rifting may be occurring, although the latter location may also be affected by magmatism. Post-breakup oceanic spreading can be observed in the central RS and GoA (e.g. Bosworth et al. 2005). Topography and bathymetry derived from the GEBCO Digital Atlas (IOC et al. 2003).

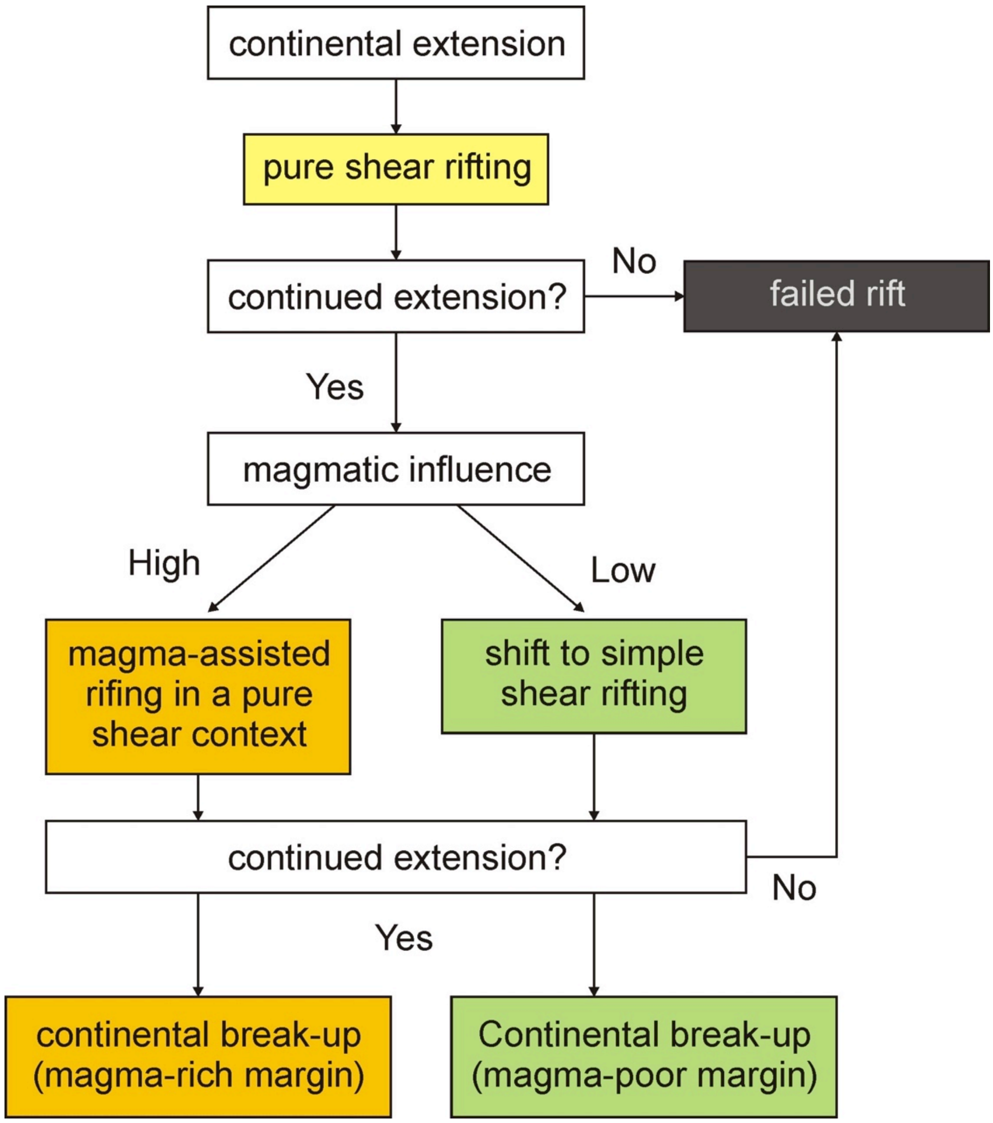

Fig. 13. Flow chart depicting the possible pathways to continental break-up as interpreted from the Afar region. Initial rifting is thought to occur in a symmetric, pure shear mode. Subsequent magmatic influence may control whether a shift to simple shear rifting occurs or not. If extension persists, the system may enter the final continental break-up phase, involving the development of a magma-rich or magma-poor passive margin. However, if extension halts before break-up, the result will be a failed rift.